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EXPLICIT CALIBRATION OF THE PILLS II
SYSTEM

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Environmental Systems Corporation

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September 1973

EXPLICIT CALIBRATION OF THE
PILLS II SYSTEM

By

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ABSTRACT

The basic characteristics of the PILLS I and II Systems are reviewed and up-dated from previous publications. Emphasis is given to the explicit calibration of PILLS II with water droplets. The operational characteristics and accuracy of the monodisperse particle generator are discussed. General procedures for deriving the particle density distribution from the measured voltage density distribution are described.

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SECTION I

CONCLUSIONS

The basic characteristics of the PILLS I and II Systems are reviewed and up-dated from previous publications. Emphasis is given to the explicit calibration of PILLS II with water droplets. The operational characteristics and accuracy of the monodisperse particle generator are discussed. General procedures for deriving the particle density distribution from the measured voltage density distribution are described.

The essential results of the calibration of PILLS II are (1) $\Delta \bar{v} = Kd^2$ where K is a constant for either of the two PILLS II scattering volumes, (2) K is independent of droplet mineral concentration up to 50,000 ppm for NaCl, and (3) errors in determination of particle density distribution of $\lesssim \pm 15\%$.

SECTION II

INTRODUCTION AND BACKGROUND

This report is an extension of work initiated under EPA Demonstration Grant No. 16131 GNK which led to a report entitled "Development and Demonstration of a Low-Level Drift Instrumentation" (No. 16131 GNK 10/71) which was published by the Environmental Protection Agency in October 1971 (Ref. 1). The purpose of that work was to demonstrate the effectiveness of cooling tower drift instrumentation which Environmental Systems had developed up to that point in time. The prime instrumentation discussed was the Particulate Instrumentation by Laser Light Scattering (PILLS I) System, although our complementary techniques of heated glass bead isokinetic sampling (IK) and sensitive paper (SP) were described fully and data from them reported. This intensive activity was initiated in March 1971 and culminated in a demonstration and seminar on September 28, 1971. The meeting was held for convenience at the Oak Ridge National Laboratory and approximately 80 persons from across the country intimately concerned with the drift problem were in attendance. The equipment demonstration was given on a mechanical draft cooling tower on air conditioning service at ORNL. Most of the measurements reported in the above-mentioned document were made on this tower.

At the time of that report, an explicit calibration of PILLS I using water droplets had not been performed. Implicit calibrations comparing the PILLS I data to complementary data obtained on a cooling tower via IK sampling and an explicit calibration using small glass spheres had been performed. Subsequently, their predictions were verified by explicit calibrations performed during 1972, wherein the PILLS I System was calibrated with monodisperse water droplets of approximate diameter 150, 300 and 500 microns. These results are described in "Design Considerations for Particulate Instrumentation by Laser Light Scattering (PILLS) Systems" which was presented at the ISA National Meeting in October 1972 and published recently in the ISA Transactions. This paper is designated as Reference 2. Although an explicit calibration of the PILLS I System was provided, the calibration was accomplished with only three particle sizes and upon equipment superceded by the PILLS II generation.

Our experience with PILLS I indicated a basic quadratic response ($\bar{v} \propto d^2$) where $\bar{v}$ is average output voltage and d is particle diameter. Furthermore, examination of Figures 17 and 19 in Reference 1 indicate two peaks in the particle density distribution near 120 and 200 μm . It is most important to note that these two peaks are evident in both PILLS I and SP data. This proved that the PILLS I system was capable of resolving particle density distribution structure of $\Delta d/d \approx \pm 0.15\%$. We presumed the same for PILLS II since its basic electro-optical design features were taken from PILLS I. Performing the present calibration experiments carefully has indicated that the PILLS II configuration, which has been used extensively in data acquisition, did not have a "peaking" voltage response for monodisperse

particles, as PILLS I apparently had, but yielded a wider range of voltage outputs for single particle diameter input. The physical reasons for this type response have recently received intensive investigation and the causes have been identified and corrected.

However, it was found that the average voltage response for PILLS II was $\bar{v} = Kd^2$, as expected. More important, determination of the basic drift parameter, particle density distribution, was obtained in a straight forward manner.

This report is an extension of the earlier report (1) and paper (2) and is limited primarily to reporting a recent explicit calibration of the PILLS II instrument. The equipment demonstrated on September 28, 1971 is now called the PILLS I System and had a single scattering volume and employed a photo-multiplier detector. Since that date there have been significant improvements in the PILLS System concept and calibration apparatus. This report describes the PILLS II generation equipment, its calibrations and data interpretation procedures. Further improvements in the equipment are being continually made but the present calibration data accurately describe the PILLS II instrument which has been used extensively for both natural and mechanical draft cooling tower drift tests in both the U. S. and Europe. The describing equations for PILLS are given, along with the defining equations relevant to the drift properties measured. These latter equations are of general utility and are independent of measurement techniques.

A more complete definition of the drift problem and a discussion of its importance are contained in our earlier report, together with a general description of the PILLS, SP, and IK techniques. We note that that part of the drift problem which the PILLS System advantageously addresses is of much greater importance than envisioned at our origination of this work over three years ago. Finally, we would like to point out that significant improvements in the IK and SP techniques have also been realized since our earlier report. These developments now enable us to use these techniques reliably in conjunction with the PILLS Systems to obtain more complete drift information.

SECTION III

REVIEW AND UPDATING OF PILLS CHARACTERISTICS

REVIEW OF PRINCIPLES AND DEFINING EQUATIONS

It is appropriate to briefly review the principles of the PILLS System concept. Figure 1 gives the schematic diagram for the PILLS II System and Figure 2 shows photographs of a prototype device. (Refer to the EPA report, Ref. 1, or to the ISA paper, Ref. 2, for a more complete description of the electro-optical elements.) The instrumentation behind the PILLS II sensor head is Environmental Systems' dual multi-channel pulse height analyzer which will be described below.

The basic operating principles of the system are simple: a single drift particle present in one of the scattering volumes at the instant of a pulse of radiation from the laser scatters light into one of the detectors and produces a voltage signal. This voltage signal is then recorded on magnetic tape or electronically analyzed and a count is stored in the appropriate channel in our multi-channel analyzer. The voltage distribution, which corresponds to the size distribution of the particles present, is obtained from the number of counts accumulated in each channel of the analyzer. Combining this measured voltage distribution and the known response function of the instrument gives the particle density distribution, the basic drift parameter measured.

Figure 1b shows a representative PILLS II output typical of either of the scattering channels. Photons scattered from the scattering volumes arrive at the off-axis detectors and produce a pulse of current which is amplified, converted into a voltage signal, stretched, and driven into a coaxial cable at the end of which the voltage monitoring and signal processing instrumentation are placed.

Because fog constitutes a very dense ensemble of small particles, having mean diameter of a few micrometers, many of them are in the scattering volume at each laser pulse. The voltage produced is often large and exhibits random fluctuations from pulse to pulse; the latter sets the practical lower limit on drift particle measurements for the system. Since the fog yield and fluctuations decrease with scattering volume size, smaller scattering volumes permit measurements to smaller drift particle sizes.

Also, the smaller the scattering volume, the smaller is the particle size which can still entertain single particle scattering. In mathematical terms, it is required that the probability of more than one drift particle in the scattering volume be very low. Typical particle density distributions decrease rapidly with increasing diameter. The lower limit set by the requirement of single particle scattering is typically much smaller than the lower limit imposed by fog fluctuations

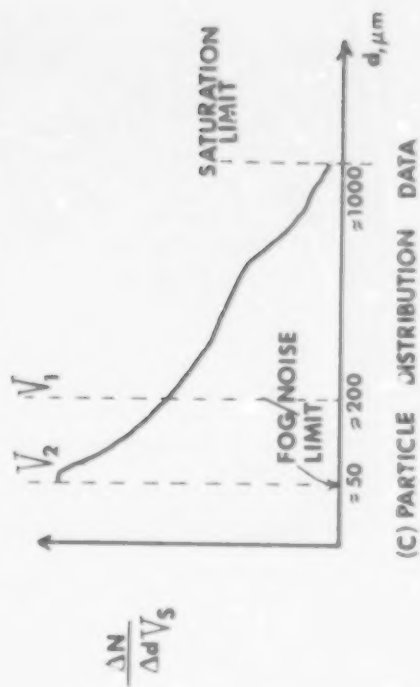
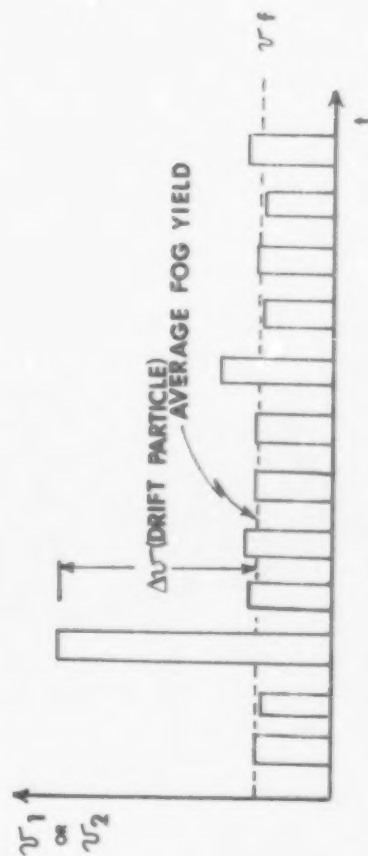
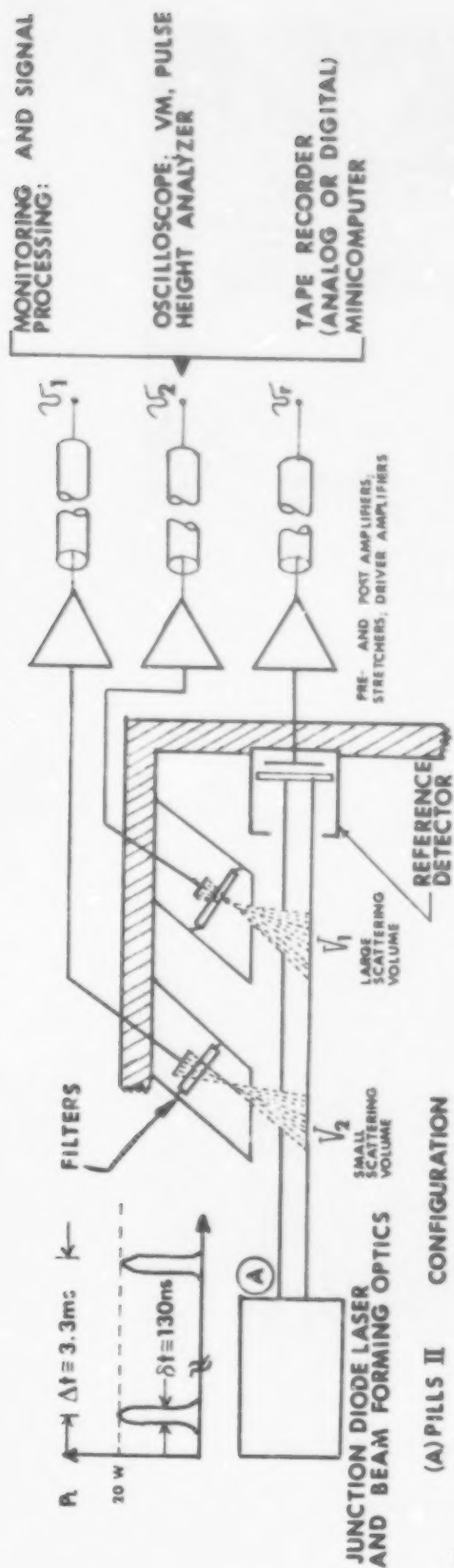
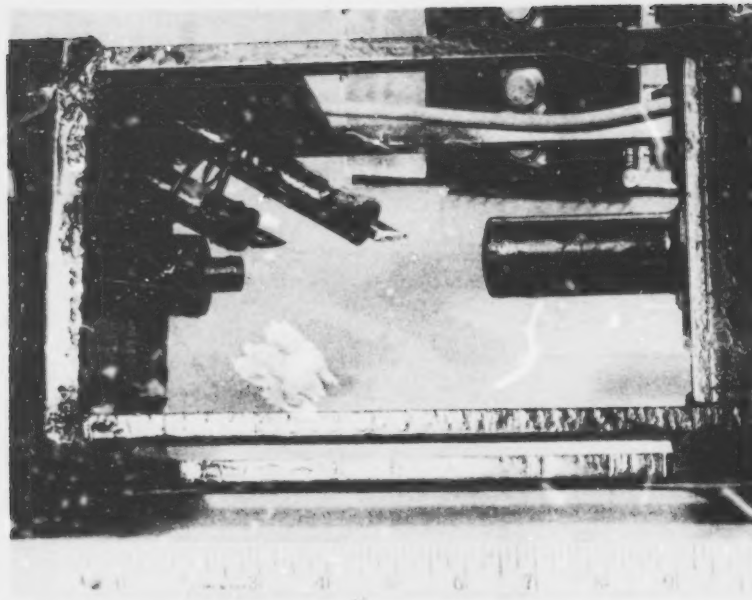
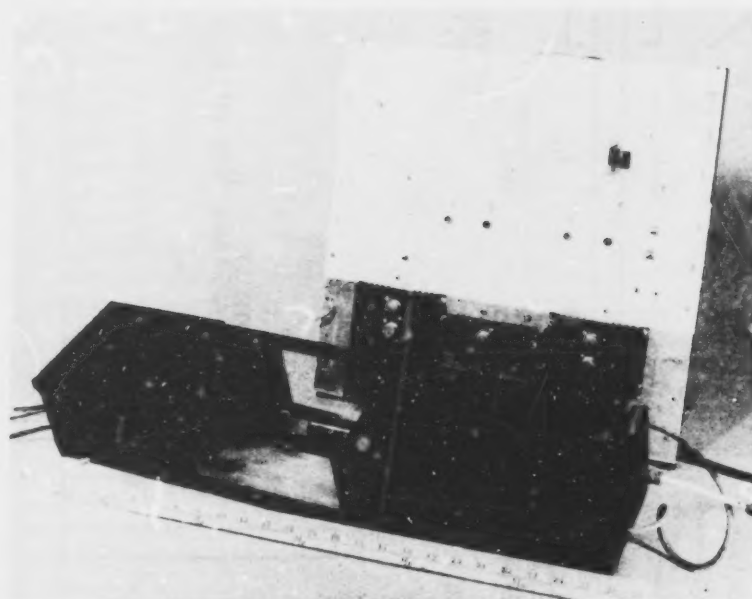


FIGURE 1

PILLS II SYSTEM
(PARTICULATE INSTRUMENTATION BY LASER LIGHT SCATTERING)



(a) Close-up of sampling volumes



(b) PILLS II and the ESC pulse height analyzer

Figure 2. PILLS II prototype

for a given scattering volume. Alternatively stated, fog fluctuations typically pose a more severe limitation on the lower practical limit than having more than one particle in the scattering volume.

However, small scattering volumes decrease the data rate for the infrequent but highly important large particles. Consequently, a wider range of drift particle size is covered by appropriate combination of a small volume which extends downward the practical range of measurements as limited by fog fluctuations on the lower end of the range and a large volume which extends upward the range, due to higher data rate, for the large particles. If the fog yield were constant, then the Δv information corresponding to the presence of a drift particle would permit subtraction down to the electronics noise limit which is about $30 \mu\text{m}$ for V_2 , the small scattering volume. Based on experience with large natural draft cooling tower measurements in the near vicinity of the drift eliminators, two independent scattering volumes of $V_1 = 1.2 \text{ cm}^3$ and $V_2 = 0.4 \text{ cm}^3$ have proven adequate and represent the configuration whose calibration is given here.

As shown on Figure 1c, we have found that the small scattering volume permits measurements from approximately 50 to $200 \mu\text{m}$ and the large scattering volume permits measurements from, typically, about $200 \mu\text{m}$ up to a limit that is either determined by saturation of the detector electronics or by physical size of the particle as compared to the laser beam. For PILLS II, the saturation limit dominates and is approximately $1,000 \mu\text{m}$. Thus we are able to cover the full range of particle diameters from 50 to $1,000 \mu\text{m}$ with good data acquisition rates and with accuracies optimized for both smaller and larger particle sizes.

In addition to fog fluctuation considerations, the pulse repetition rate and the scattering volume transverse dimension d_t in the direction of the flow must be so chosen that a given entrained particle will not be counted more than once by successive laser pulses. That is,

$$u\Delta t > d_t. \quad (1)$$

It is readily seen that this relation is satisfied for the flow velocities $u > 4 \text{ m/s}$ and repetition rates of $300 \text{ Hz} = 1/\Delta t$. This is confirmed experimentally in the field by observing that in very few instances does one observe multiple pulses.

The basic measured output from the PILLS System is the voltage density distribution for the voltages Δv above the average fog yield which are produced by single drift particles and which are recorded in the field with the PHA or produced with minicomputer processing of field-recorded magnetic tapes as described later. Formally, if matrix $R(v;d)$ represents the PILLS voltage response to particles of diameter d and matrix $P(d)$ is the actual particle density distribution, then the measured voltage distribution $Q(v)$ is given by

$$\underline{Q}(v) = \underline{R}(v;d) \underline{P}(d). \quad (2)$$

Since $\underline{Q}$ and $\underline{R}$ are known by field and calibration measurements, $\underline{P}(d)$ is determined according to

$$\underline{P}(d) = \underline{R}^{-1}(v;d) \underline{Q}(v). \quad (3)$$

Although the relationship between an output voltage pulse and an input particle of size d is not unique, or one-to-one unless $R(v;d)$ corresponds to the mathematically ideal "impulse or delta function" response, the drift statistical properties, i.e., particle density distribution are rigorously determined with minor restrictions in the class of allowable matrix element functions in $P(d)$. These procedures require, in general, use of numerical methods.

Equation (2) can also be formulated in terms of an integral equation:

$$q(v) = \int_{d_{\min}}^{d_{\max}} r(v;d)p(d)dd \quad (4)$$

where now q , r , and p are normalized probability densities per unit volume.

Thus, the principal objective of calibration is accurate determination of the instrument response.

Rather than employing matrix or integral equation inversion for high volume data reduction, we have discovered, developed, and applied extensively a simpler, approximate data analysis technique which obviates the use of digital computers. Procedurally, a predicted particle density distribution is determined according to

$$\begin{aligned} p'(d)dd &= q(v)dv \\ &= q(Kd^2) 2Kd dd \end{aligned} \quad (5)$$

The interpretation of (5) is that we assume the number of voltage pulses in the voltage interval $(v, v + dv)$ is exactly equal to the number of particles in the interval $(d, d + dd)$ where $v = Kd^2$ defines a unique relationship between the interval end points. Alternatively stated, this amounts to assuming that the instrument response is described by

$$r(v;d) = \delta(v - Kd^2) \quad (6)$$

which is the ideal case.

This technique gives satisfactory engineering results. As will be seen, the instrument response function may be approximately modeled as

$$r(v;d) = 1/v_d e^{-v/v_d} \quad (7)$$

where

$$v_d = \bar{v} = Kd^2 \quad (8)$$

For this type response and for $p(d) \propto 1/d^\alpha$ a closed-form analytical treatment is possible and it can be shown by direct substitution that

$$\frac{p'(d)}{p(d)} \longrightarrow C(\alpha), \text{ large } d \quad (9)$$

where $C(\alpha)$ is a constant depending on α .

Thus for "power law" particle density distribution, for example, this technique is precise for large d since inspection of the $p'(d)$ or $q(v)$ data indicates the value of α from which $C(\alpha)$ is then determined. $C(\alpha) = 1, 1.3, 2,$ and 3.3 for $\alpha = 3, 4, 5,$ and 6 respectively.

We have employed this technique extensively in the reduction of data. A most encouraging experimental fact has been the good agreement between PILLS II data reduced as described and SP data in the overlapping range where both give $p(d)$. This good experimental agreement via two completely independent measurement techniques verifies the assumptions made in Equation (5). Precise results, as noted, are obtainable for typical and mathematically well-behaved particle density distributions.

As with any physical measurement, the accuracy of the PILLS System is related to the accuracy of the calibration and maintenance of calibration conditions during field operations. Calibration particle sizes are known to within $\pm 5\%$ and field and laboratory voltage measurements are readily made to within $\pm 5\%$. The number of counts in a given voltage channel is very accurately known. Assuming $\pm 5\%$ errors to allow for voltage drifts, departures from linearity and fog fluctuation effects, the determination of the number of particles in a given interval $(d, d+\Delta d)$ is taken as $\leq \pm 15\%$. Although a thorough error analysis has not been made, we conclude that $\pm 15\%$ represents the operational errors of the PILLS II System in making drift particle

density distribution measurements over the range $50 < d < 1000 \mu\text{m}$ when sufficient counts are obtained to permit good statistical definition of the measured voltage density distribution.

We now define the measured drift parameters and discuss the improvements in the system. The PILLS II equipment is operated for a period T of, for example, one hour during which a total volume V_s is sampled according to:

$$V_s = V_{1,2} T/\Delta t = \frac{1.2 \times 3.6 \times 10^3}{0.4 \times 3.6 \times 10^3} : \frac{3.33 \times 10^{-3}}{3.33 \times 10^{-3}} = 1.30 \text{ m}^3/\text{hr}, V_1 \quad (10)$$

$$= 0.43 \text{ m}^3/\text{hr}, V_2$$

Interestingly, the repetitively-sampled, non-contiguous scattering volumes can be called "PILL-BOXES".

The number of voltage pulses in a given voltage interval is converted, via the instrument response, into the number of particles having diameter d_i in the associated size interval Δd_i . This information, with knowledge of the total volume sampled V_s , leads to the particle density distribution:

$$P(d_i) = \frac{\Delta N_i}{\Delta d \cdot V_s} \left\{ \frac{\#}{\mu\text{m} \cdot \text{m}^3} \right\} \quad (11)$$

Note that the i subscript has been omitted where it is redundant; this practice will be continued in remaining definitions. Note also that "density" refers to the number of particles in a given range per unit volume and that "distribution" refers to the manner in which the total number of particles per unit volume is distributed over the range of diameters of interest. The present uses of these adjectives are to be clearly distinguished from the conventional statistical usages wherein, for example, $p(d)$ is the probability density per unit volume and the

probability distribution per unit volume is $\int_0^d p(d)dd$. Note that $\int_0^{d_n} p(d)dd \rightarrow 1$ as $d_n \rightarrow \infty$.

The mass density distribution is easily derived from the particle density distribution according to:

$$\frac{\Delta X_i}{\Delta d} \triangleq \frac{\pi}{6} \bar{d}_i^3 \frac{\Delta N_i}{\Delta d \cdot V_s} \left\{ \frac{\text{gms}}{\mu\text{m} \cdot \text{m}^3} \right\} \quad (12)$$

where s is the specific mass (gm/cm^3) of the particles and $\bar{d}_i$ is the mean diameter of the particles in the range Δd_i . The total mass density is therefore realized by summation over the applicable ranges of particle size measured:

$$X = \sum_i \Delta X_i = \frac{\pi s}{6} \sum_i \bar{d}_i^3 \frac{\Delta N_i}{\Delta d \cdot V_s} \Delta d_i \quad \{\text{gm/m}^3\} \quad (13)$$

It is to be noted for emphasis that each of these definitions relates to a specific measurement point "j" in the tower.

A derived parameter of considerable utility is the mass flux distribution defined by:

$$\left(\frac{\Delta D}{\Delta d}\right)_j = \frac{\Delta X_i}{\Delta d} \cdot u_{ij} = \frac{\pi s}{6} \bar{d}_i^3 \frac{\Delta N_i}{\Delta d \cdot V_s} u_{ij} \quad \left\{ \frac{\text{gm}}{\mu\text{m} \cdot \text{m}^2 \cdot \text{sec}} \right\} \quad (14)$$

where u_{ij} is the absolute particle speed in meters/sec normal to the measurement plane and associated with the i^{th} particle size and the j^{th} measurement station. The drift mass flux is then

$$\begin{aligned} \Delta D_j &= \sum_i \left(\frac{\Delta D}{\Delta d}\right)_j \cdot \Delta d_i \\ &= \pi s / 6 \sum_i u_{ij} \bar{d}_i^3 \frac{\Delta N_i}{\Delta d \cdot V_s} \cdot \Delta d_i \quad (\text{gm}/\pi^2 \cdot \text{sec}) \end{aligned} \quad (15)$$

and the total mass emission is:

$$\begin{aligned} D &= \sum_j \Delta D_j \cdot A_j = \\ &= \sum_j \left[A_j \sum_i u_{ij} \left(\pi / 6 s \bar{d}_i^3 \frac{\Delta N_i}{\Delta d \cdot V_s} \right) \Delta d_i \right] \quad (\text{gms/sec}) \end{aligned} \quad (16)$$

where A_j represents the appropriately-chosen segments of the total emitting surface area across which the drift particles are transported. The u_{ij} velocity components must be representative of the i^{th} size particle absolute velocities in the A_j area.

Historically, the total drift emission of a cooling tower has been characterized as a percentage of the circulating water rate R in grams/sec and is therefore given by:

$$\Delta = D/R \times 100\%$$

(17)

For completeness, it is appropriate to define a specific drift fraction δ which is applicable for measurements made in the immediate vicinity of the drift eliminators and is more appropriate for counter-flow than cross-flow towers. The specific drift fraction is the mass flux at a given location near the drift eliminators divided by the water loading per unit area of drift eliminators associated with that location.

IMPROVEMENTS

The improvements in the PILLS II System over the PILLS I System are briefly summarized in the following paragraphs. It is interesting to examine the recommendations for further work in the October 1971 report for comparison with the improvements actually made.

Explicit Calibration

As noted above, explicit calibration using water droplets had not been realized by October 1971. This is the principle subject of this report and is discussed in succeeding sections.

Improvements in Field Reliability

The PILLS I System was a developmental device whose basic optical configuration could be varied but which lacked the rigidity necessary for a routinely operational field device. The various angles and distances as determined from the PILLS I instrument were chosen as the basic inputs for the design of PILLS II which, upon comparison, can be seen to be more rigid and smaller in physical size. In addition, the troublesome and noisy photomultiplier detector in PILLS I was replaced with a semiconductor photodetector in conjunction with a high current gain, low noise amplifier circuit whose overall performance is superior to that of the photomultiplier for the 9040 Å radiation. As a consequence of these and other improvements, the PILLS II System has logged more than 1,000 hours with minimal down time in operational cooling towers. In a recent test in a natural draft unit, the system remained inside for a continuous period of more than 400 hours.

Fog Suppression

As indicated schematically on Figure 1 and discussed above, the high density of fog particles having mean diameter of a few microns produces a scattered component of light each time the laser fires; this is termed the fog yield. The fog yield voltage is approximately proportional to

the size of the scattering volume and, as pointed out above, if it were constant over a period embracing several laser pulses (a few milliseconds), then the single drift particle information extending to smaller sizes could be realized by subtracting out the fog yield. Alternatively stated, fog fluctuations set the lower practical limit for meaningful drift particle measurements and, as a consequence, small scattering volumes permit smaller practical measurements of drift particle size. However, small scattering volumes have lower data rate for the infrequent large particles. Accordingly, we have found that the two completely independent scattering volumes described above permit measurements from about 50 microns up to 1,000 microns in typical cooling tower fogs and with sampling intervals of a few hours. But the fog yield fluctuations may also be minimized in signal processing, as discussed next. Indeed, the extraction of meaningful information from the "fog plus drift particle" pulses has had a major influence in the design of signal processing techniques and equipment.

Signal Processing

PILLS I data were recorded by the "brute force" technique of setting a precision oscilloscope trigger level slightly above the maximum excursion of fog yield and recording, in the single sweep mode, on photographic film the individual fog plus drift particle pulses. Although slow and tedious as compared to techniques presently employed with PILLS II, this technique allowed accurate and easily interpretable voltage measurements.

PILLS II data are now routinely acquired with the two following complementary recording/processing techniques: (1) field pulse height analyzer and (2) analog tape recording/minicomputer processing.

The Environmental Systems' dual 10-channel pulse height analyzer was specifically designed and fabricated to accommodate the output of the PILLS scattering channels. The analyzer records the number of voltage pulses whose excursion above the average fog level falls within the adjustable voltage intervals of the analyzer. The average fog yield is established by long time constant, analog circuitry (termed the "fog cancellation circuit") which precedes the voltage height analysis section of the PHA.

This device permits true on-line acquisition of data and has proven extremely valuable in the exploratory determination of test point position within a cooling tower as well as sampling time duration. The data are "read out" by means of a single light emitting diode indicator which is connected sequentially with the outputs of decade counters in each of the dual 10 channels. The PHA data are especially valuable for large particles which require long sampling times for adequate statistical counts. Routinely, we leave the PILLS II/PHA System in operation overnight and unattended, a most effective way to collect data! The analog fog

cancellation circuitry does not permit extension to drift particles as small as does the computer processing of the tapes described next. The PHA data are of prime use for the large particles in each of the scattering volumes as realized with long periods of data collection, as in an overnight run.

An FM cassette magnetic tape recorder is used to collect the PILLS output pulse train in an analog fashion. The outputs of the two scattering channels plus the reference detector output are recorded. The tapes are then returned to the computer lab wherein a minicomputer examines these analog outputs and extracts the drift particle data in each of the two scattering channels in the following way. First, each scattering volume pulse is normalized to the laser power for that pulse, thus removing peak to peak variations in laser power down to the noise limit of the detectors and amplifiers. Next, each normalized pulse is defined as a drift pulse ("B" in Figure 1b) and the average of the pre- and post-pulses ("A" and "C" in Figure 1b) is subtracted from it. The value of this voltage difference is then determined and stored in one of two thousand channels corresponding to voltage height. According to this algorithm, the minicomputer then produces the net voltage distribution from which the particle density distribution may be derived.

The minicomputer software and PILLS II hardware have been so configured that the intermediate step of analog tape recording can be omitted and the minicomputer can operate upon the PILLS II output in a truly on-line fashion, giving the voltage distribution immediately after (or during) a test.

We have also developed the capability of digitally recording the voltage pulses on magnetic tape. This capability eliminates the usual problems of variations of gain in analog recording. Also, computers can more readily digest digital information than the analog form; indeed, the analog data must first be digitized for a computer to digest it. This technique will be routinely employed in the future when a field tape record is required.

In conclusion, the PILLS II System whose calibration is reported here represents substantial improvements over the PILLS I device with regard to field reliability, range of practical measurements, and signal recording/processing capabilities. More important, our understanding of the electro-optic properties of the device have advanced considerably as has our understanding of the drift data produced by it.

Improvements of equal magnitude in both the sensitive paper technique and the isokinetic sampling technique have also been realized since the October 1971 report. Numerous intensive tests involving all three techniques have been performed and the data thereby generated are now being "fed into the system" for evaluation of the feasibility of,

particularly, salt water, natural draft cooling towers. It is most important to note that, in addition to being complementary, the data generated by these three techniques exhibit a high degree of internal consistency and good agreement when compared to each other in common terms.

SECTION IV

DESCRIPTION OF CALIBRATION APPARATUS

It is well known that a highly monodisperse beam of liquid droplets can be generated by vibrating orifice techniques which exploit the inherent instability of a fluid jet interacting with a viscous medium, (References 3 and 4). Our initial attempts with these techniques were with the Princeton Fluidics Corporation earphone driven, longitudinally vibrating, orifices. Although we were able to calibrate the PILLS I device with three particle sizes as discussed in Reference 2, this equipment proved unreliable and particles over the entire range of interest could not be generated.

It proved necessary for us to completely develop the particle generating technology ourselves. Two laboratory visits at the University of Minnesota and the University of Illinois proved very helpful and acknowledgements are made of the discussions with Drs. Benjamin Liu and Richard Bergland of the University of Minnesota and with Dr. Charles H. Hendricks and Mr. Chris Foster of the Charged Particle Research Laboratory at the University of Illinois. In addition to learning how to reliably and controllably generate monodisperse beams from 15 to 700 microns using transversely vibrating glass orifices, it was necessary to develop separation techniques so that one particle of the prescribed size could be admitted to the scattering volume at a time. It was found that roughly one thousand volts DC applied to a charging collar near the nozzle exit and through which the particles are projected permitted a charge to be applied to each of the droplets.

Unless the particles were deflected as described below, this voltage would produce a rapid spatial dispersion of the droplets which were then allowed to fall through the appropriate scattering volume. The single particle occupancy condition was certified by inspection of the output of that channel. This technique was employed in the data reported here.

Considerable time was spent in attempts to electrostatically deflect single particles out of the monodisperse beam by applying several hundred volt pulses to deflector plates immediately following the charging collar. Although this is relatively easily done for particles in the range of 70 to 300 microns, it becomes increasingly difficult for both larger and smaller particles. Figure 3 shows a schematic diagram of the calibration apparatus as used for these tests. Figure 4 is a photograph of the principal components of the equipment. The orifices are produced by heating and drawing down to a small diameter standard Pyrex tubing. The ends are then polished off squarely using an abrasive. As a rough estimate, the particle size generated by a particular nozzle exit diameter will be about twice the nozzle diameter. These nozzles are then mounted upon electrical bimorphs which flex in a bending mode upon the application of a voltage across the insulated dissimilar materials. Specific particle sizes are realized by "cut and try" on the preparation of the nozzles and by minor variations of the frequency and pressure parameters. As an example, a 50 micron orifice will generate roughly a 100 micron droplet when the frequency is 20 KHz and the pressure is 10 psi.

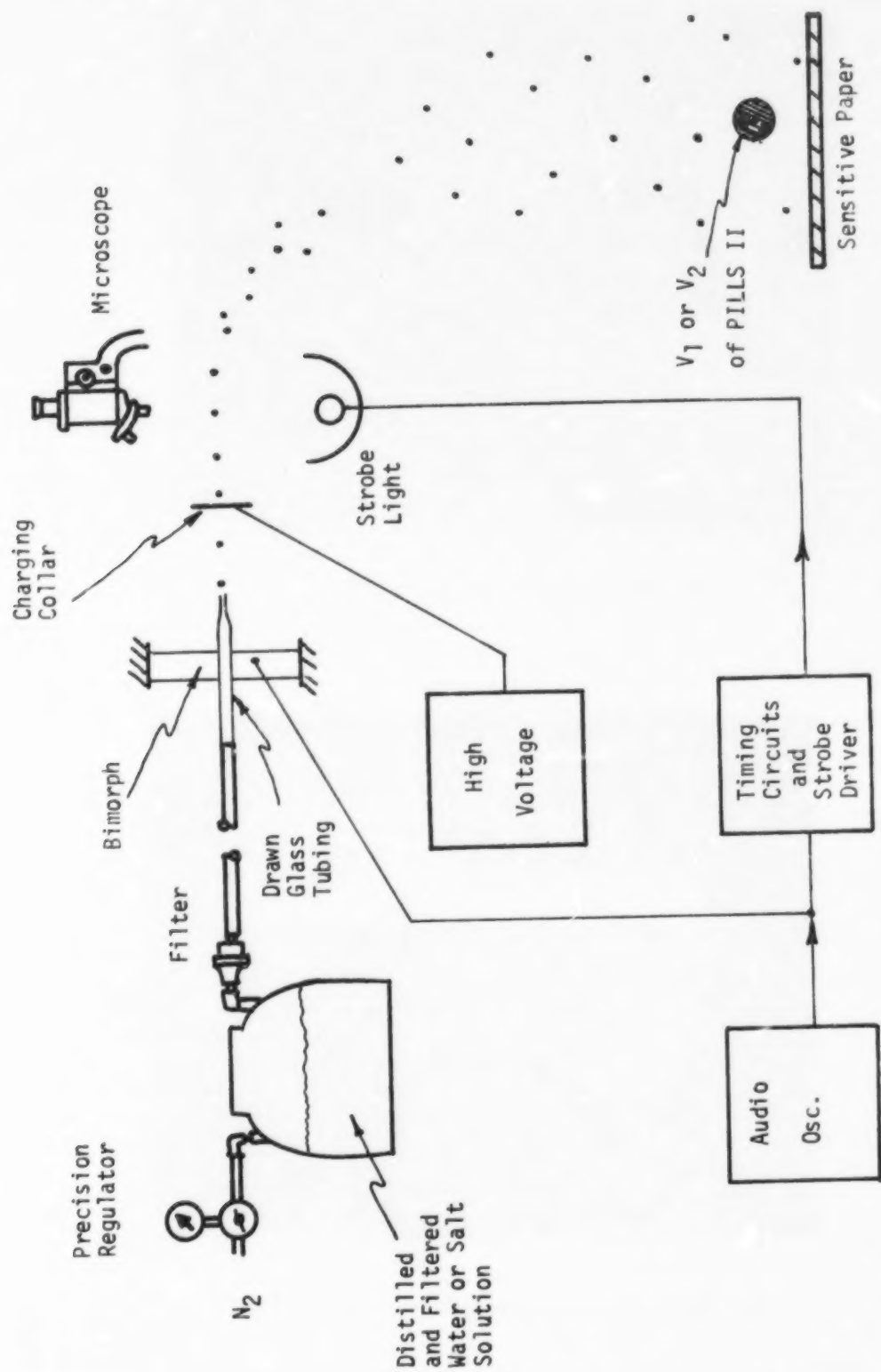
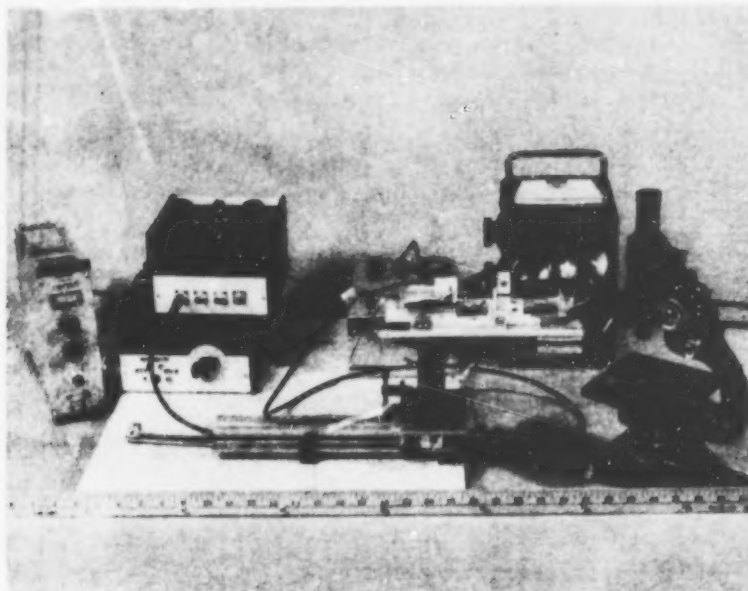
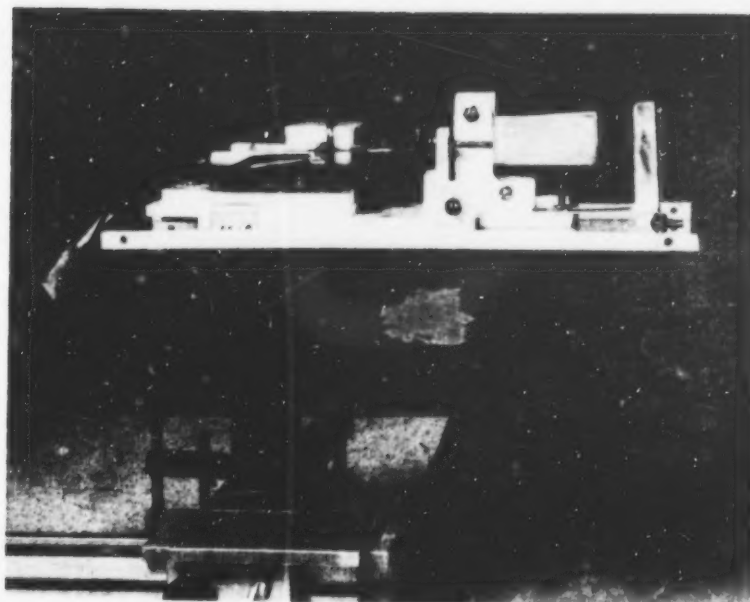


FIGURE 3. CALIBRATION APPARATUS



(a) General view of apparatus



(b) Close-up of jet and deflection plates

Figure 4. Monodisperse Particle Generator

Larger particles require lower frequencies and lower pressures and are easier to generate. Small particles, in the range of 15 to 50 microns, are more difficult to generate and observe. The importance of having very clean solution should not be underestimated. Clogged nozzles can usually be opened by forcing alcohol backwards into the nozzle with a syringe.

The strobe lighting of the particles is essential for optimum adjustment of the frequency and pressure. Satisfactory operating conditions are represented by uniformly sized and spaced particles with no small satellite droplets. A useful test of the nozzle prior to cementing it on the bimorph is to observe the distance that the free jet will project before breakup; the greater the distance of the unbroken free jet, the easier it is to generate a monodisperse beam.

Particle size is determined in two ways: (1) via a calibrated reticule in the microscope and (2) by collecting a few milliliters from the jet and dividing by the known number of particles in the collection; over most of the particle size range of interest one particle is produced per cycle of the oscillator wave form. This relationship is usually true but must be carefully checked since it is possible for two particles per cycle to be produced. The independently determined diameters of the droplets agree within better than $\pm 5\%$.

Figure 5 shows a stream of approximately 300 micron particles. The photograph was made very near to the exit of the nozzle. No charging was applied. Note the oscillatory shape of the droplets which is typical for distances within a few centimeters of the nozzle.

When the droplets are dispersed by application of high voltage to the charging ring, the angle of dispersion depends upon the particle size and the voltage applied. Typically, 1000 volts are required to disperse a 100 micron beam into an area several inches in diameter.

This apparatus has been essential for calibration of our other drift measurement apparatus as well. The sensitive paper machine exhibits a strong impingement velocity dependence of the stain size versus particle size. Further, the trapping efficiency as a function of particle size of our heated IK tubes has been determined with this droplet generator. Finally, the equipment has also been used in generating opaque liquid droplets.

In conclusion, although the principles of vibratory capillary particle generation are easily understood, operation of such equipment rapidly becomes more art than science, especially when particles are deflected by electro-static means from the main beam. Stated more practically, it is very easy to underestimate the difficulty and expense of the application of these straightforward techniques.

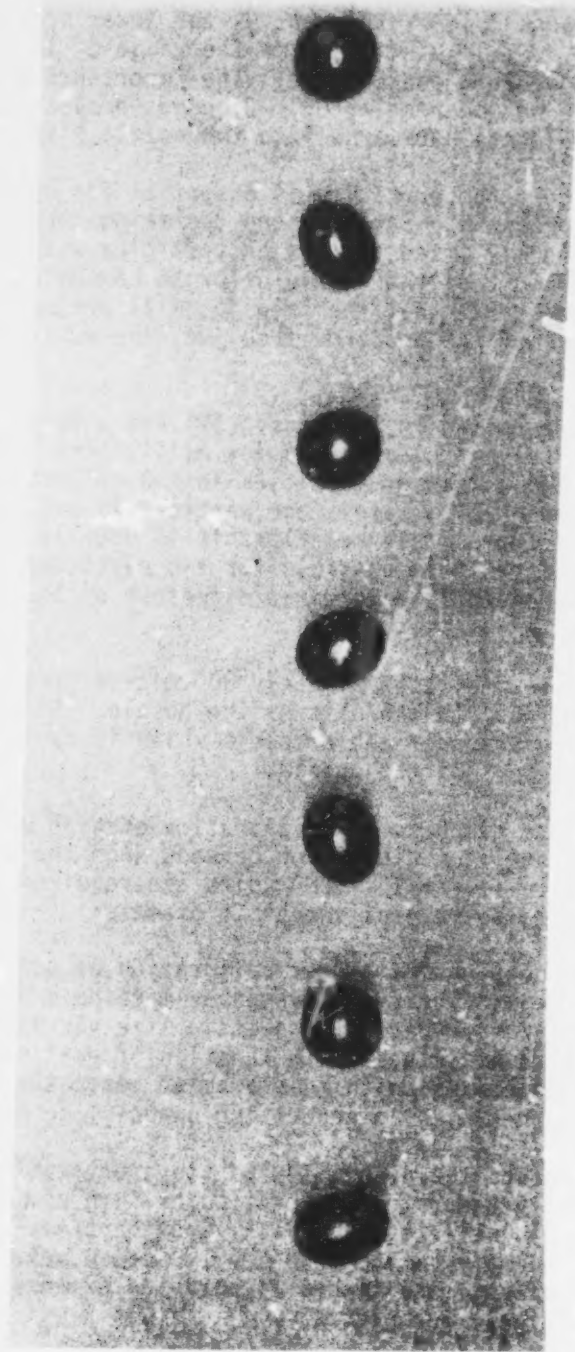


Figure 5. 300 μm droplets near the exit of the vibrating jet

SECTION V

CALIBRATION PROCEDURES AND RESULTS FOR PILLS II

PROCEDURES

Since both the PILLS II System and the calibration apparatus have been described in the two previous sections, the results can be concisely presented. Procedurally, the calibration apparatus was set up to generate a horizontal beam of particles which was then dispersed with the charging ring as shown in Figure 3. One or the other of the scattering volume outputs was monitored with an oscilloscope/camera system for the bulk of the measurements. More recently, calibrations have been effected using the dual 10-channel pulse height analyzer.

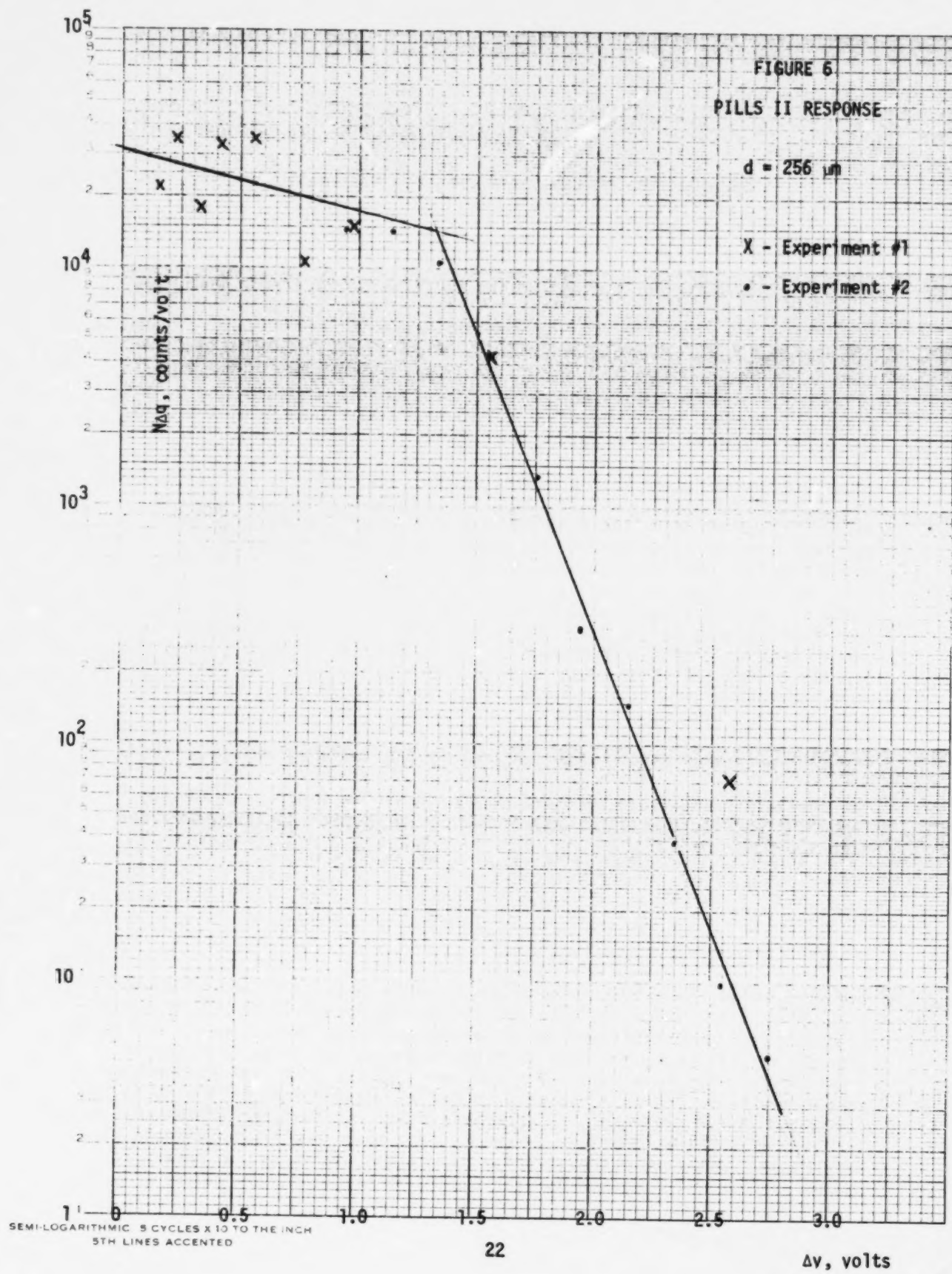
The dispersed particle beam proceeds several centimeters, depending upon the size of the particles. The particles approach terminal settling velocity as they reach the scattering volume under concern. Single particle scattering is ensured by requiring the particle pulse rate to be significantly lower than the repetition rate of the laser. Uniformity of the dispersed particle beam is tested by allowing the particles to fall on discs of sensitive paper placed below the sampling area. It is required that each portion of the sampling volume under calibration have equal probability of particle occupancy. This is ensured by making the stain density of the sensitive paper uniform. Also, the fact that the particles have the same size as the point at which they are measured is verified with the sensitive paper. Due to the inherently "wet" nature of the air around the dispersed beam, no evaporation effects were observed as expected for the relatively large particles used in the calibration.

The particle pulses were recorded using the single sweep oscilloscope technique on Polaroid film. Approximately 200 pulses for each particle size were obtained.

RESULTS

Determination of Response Function

Figure 6 shows the output voltage distribution when particles of diameter $d = 256 \mu\text{m}$ were introduced into the large scattering volume. This experiment was performed with the PHA and would have been impractically difficult without it. It is to be noted that the response for large voltages is approximated well by a relation $r(v;d) \sim e^{-v/v_d}$. Since for exponential response $v_d = \bar{v}$, the calibration data can be systematized according to the parameter v_d . But $\bar{v} = Kd^2$, as described below, so that the system response is described if the constants K_1 and K_2 , for large and small channels, are determined. Although mathematically convenient, it is not necessary to assume exponential response for the family of $r(v;d)$ curves (where d is the



parameter) may be used directly in numerical evaluations. We have employed this numerical technique in the reduction of critically important data for which maximum accuracy was essential but utilize the approximate technique discussed in Section II more routinely.

Determination of K_1 and K_2

Figure 7 shows the resultant average output voltage versus particle size for the PILLS II System. It should be pointed out that these are the net stretcher output voltages (as appears at the end of the coaxial single cables) versus diameter relationship and are routinely used for the reduction of data. This calibration thus represents the average voltage response over the particle size range from 60 to 700 microns. It is seen that both curves fit well to a Kd^2 relationship. Accordingly, the values of K and the range over which they apply are:

$$K_1 = 1.0 \times 10^{-5} \text{ V}/\mu\text{m}^2, 100 < d < 1000 \mu\text{m}$$

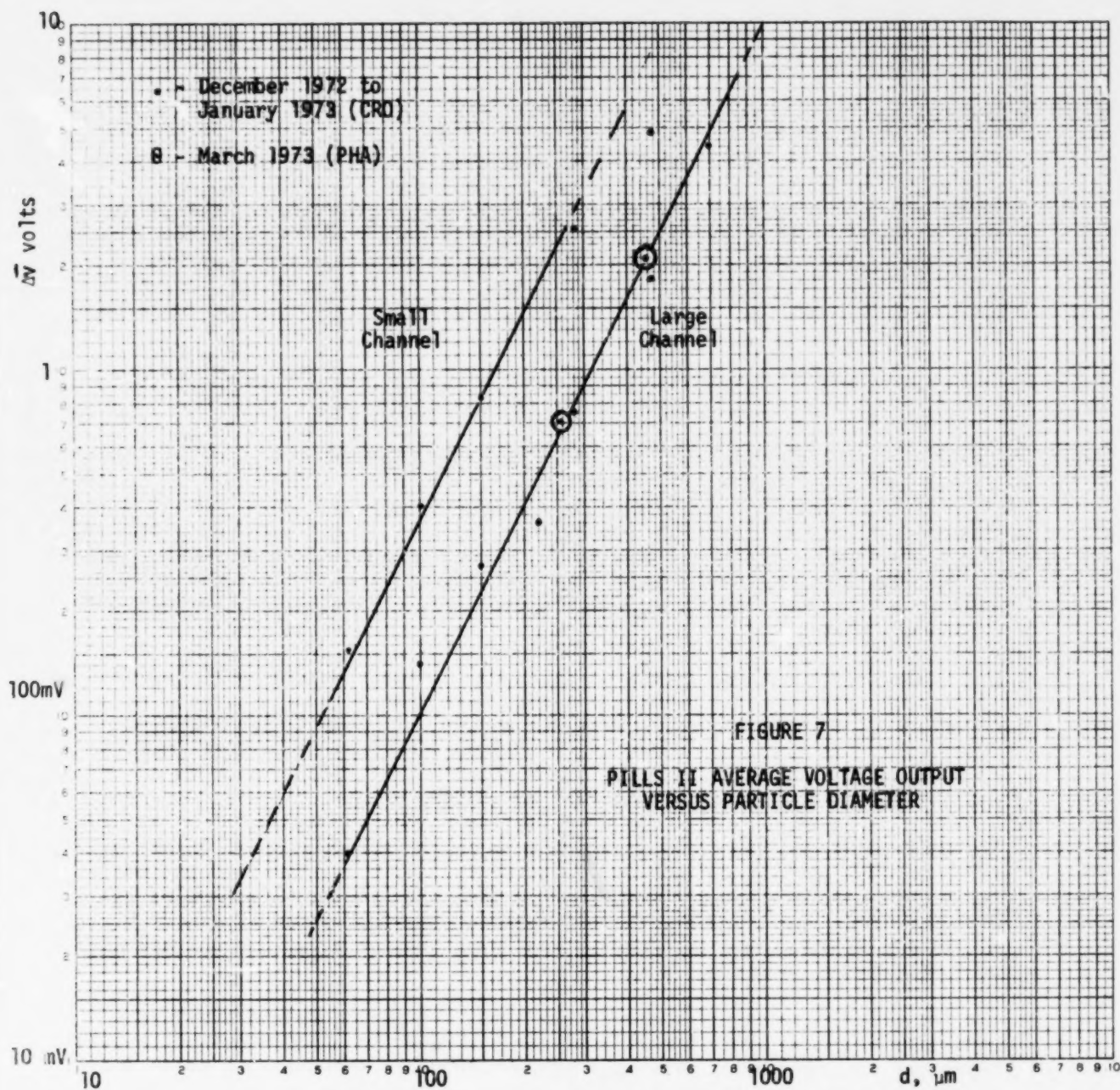
$$K_2 = 3.6 \times 10^{-5} \text{ V}/\mu\text{m}^2, 50 < d < 300 \mu\text{m}$$

Accuracy of particle sizes is better than $\pm 5\%$ and voltage determinations are better than $\pm 5\%$. Multiple repetitions of each data point to determine "error trees" were not performed due to time consumption; each point represents at least two man days just to acquire the raw data. Repeatability is good, as explained later.

Each data point on these curves is produced by simple averaging of approximately 200 voltages, excluding the values less than 5% of the maximum value observed. The principal basis for this approach is that it leads to the expected Kd^2 relationship. Smaller or larger fractions would also lead to this relation but would have been impractically difficult to measure or would have omitted a significant fraction of the pulses.

The data point for the small scattering volume at 470 microns is below the straight line portion defined by the other four data points since the small scattering volume stretcher departs from linearity in the neighborhood of 3 to 4 volts. The circuitry for the large scattering volume is linear to approximately 10 volts, thus making the large scattering volume extrapolatable to 1,000 micron particle diameter.

The encircled data points shown on the large scattering volume curve were generated with the pulse height analyzer equipment in a post-test calibration performed several months after the other data were generated and after the system had been used in several field tests and operated for a total period of roughly ten weeks in operating cooling towers. It is to be concluded that the calibration is repeatable and the PILLS II characteristics did not shift during field use.



Effects of Dissolved Salts

An experiment was performed to determine the effect upon the calibration of high concentrations of salt dissolved in the water droplets. Procedurally, a beam of pure water droplets, $d = 108 \mu\text{m}$, with no electrostatic dispersion was admitted at a fixed location in the large scattering volume to produce a reference voltage. Multiple particle scattering was realized for this undispersed beam case; nominally, 5 particles were in the scattering volume. The particle generator and PILLS System were mounted in fixed positions and the particle size and resultant voltage observed and recorded.

The distilled water in the particle generator reservoir was then exchanged for 50,000 ppm NaCl solution. It was then verified that the salt solution particle size was identical with that of the pure water droplets. The resultant voltage was also identical, leading to the conclusion that salt concentrations up to 50,000 ppm do not affect the calibration of the PILLS instrument. The practical consequence of this result is that the calibration can be expected to hold independent of mineral concentrations when the PILLS System is employed in brackish or sea water applications.

SECTION VI

REFERENCES

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SECTION VII

GLOSSARY

A_j	=	portion of total emitted surface area
$C(\alpha)$	=	constant
d	=	particle diameter
Δd	=	incremental diameter
$\bar{d}_i$	=	mean diameter of the particles
d_t	=	scattering volume transverse dimension
D	=	mass emission
IK	=	isokinetic sampling instrument
K	=	constant for either PILLS II scattering volumes
ΔN_i	=	number of particles in i^{th} size element
$p(d)$	=	normalized true particle probability density per unit volume
$\underline{P}(d)$	=	actual particle density distribution
$p'(d)$	=	predicted particle density distribution
$q(v)$	=	normalized voltage distribution per unit volume
$\underline{Q}(v)$	=	measured voltage distribution
$\underline{R}(v;d)$	=	matrix representation of instrument response function
R	=	circulating water rate
s	=	specific mass
SP	=	sensitive paper particulate instrumentation apparatus
T	=	duration of measurement interval
Δt	=	time between pulses of LASER
u	=	air flow velocity
u_{ij}	=	absolute particle speed

V_1 = large scattering volume
 V_2 = small scattering volume
 $\bar{V}$ = average voltage response
 Δv = incremental voltage
 v_d = average voltage response for diameter d
 V_s = volume sampled

α = constant describing power law function
 Δ = total drift emission
 δ = specific drift fraction
 χ = total mass density
 ΔX_i = mass of i^{th} size element